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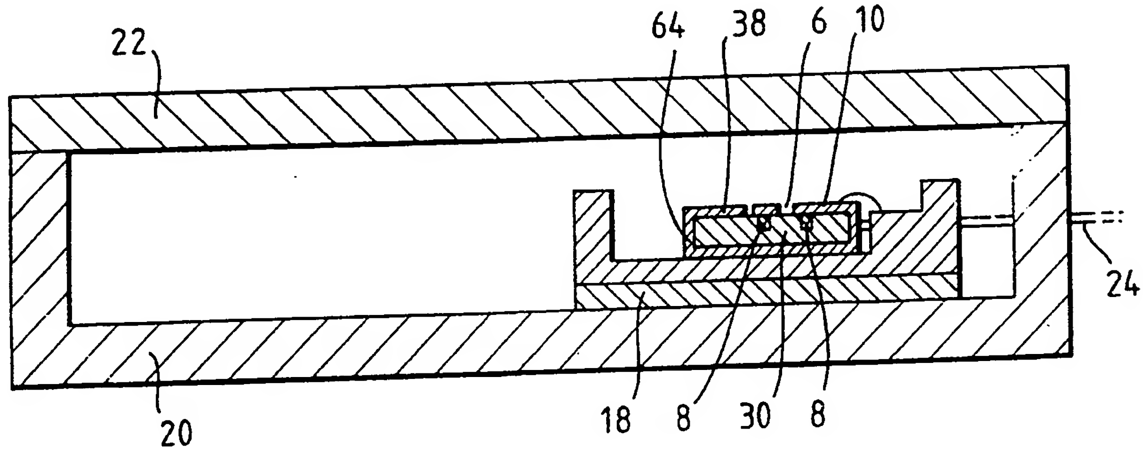

(57) Abstract

An optical modulator (30) has a hot electrode (12) and a single ground plane electrode (64) which is close to the hot electrode on the upper surface (6). This form of travelling wave electrode (12, 64) confines the substrate modes to rectangular waveguide modes so providing a higher frequency response to the modulator (30) by moving the first substrate modes to a higher frequency.

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OPTICAL MODULATORS

This invention relates to optical modulators.

Optical modulators are devices for modulating an optical signal, for example its phase, amplitude or frequency. One class of optical modulators used for high speed operation comprises a substrate of an electro-optically active material having an optical waveguide and a travelling wave electrode structure in which the microwave velocity is matched the optical velocity. The microwave signal develops an electric field between hot and ground electrodes in a region of the waveguide so affecting its optical properties and hence influencing any optical signal co-propagating with it. Such modulators include phase modulators, Mach-Zehnder modulators and directional couplers.

Such known modulators are adversely affected by moisture and are temperature sensitive. The modulators are therefore hermetically sealed within a robust metal housing having a laser welded lid, often with a peltier cooling element to stabilize its temperature.

The high frequency performance of such devices has been found to be limited by dips in the optical modulation frequency spectrum.

The present invention seeks to provide an optical modulator having an improved high frequency response. Accordingly, an optical modulator comprises a substrate of an electrooptically active material having an optical

waveguide and travelling wave electrodes including a hot electrode for applying an electric field to the optical waveguide in an active region extending in substantially one direction on a first surface of the substrate characterised in that there is single ground plane electrode which extends from near opposite sides of the hot electrode and bounds each surface of the substrate which extends substantially parallel with the active region other than the first surface.

The use of a single ground plane which bounds each of the surfaces of the substrate which extends substantially parallel with the hot electrode prevents unwanted propagating microwave modes within the bulk substrate electrooptic material. For convenience these unwanted modes will be referred to as microstrip substrate modes to distinguish them from the coplanar transmission line modes between the hot electrode and the coplanar ground plane travelling wave electrodes which modulate the electrooptical properties of the waveguide.

The single ground plane of the present invention substantially confines the microstrip modes to rectangular waveguide modes.

The single ground plane may comprise a pair of ground electrodes formed on the first surface of the substrate each electrically connected to a metal enclosure. For a rectangular ground plane close to the substrate the low frequency cut-off is given by

$$\nu_{cut\text{-}off} = c/(2\alpha\epsilon^{1/2})$$

where α is the rectangular waveguide width, ϵ is the substrate dielectric constant and c is the speed of light.

By using an appropriately dimensioned substrate with a ground plane close to its sides, the cut-off frequency can be made higher than previously obtainable in prior art packaged devices as there are no resonant modes coupling energy from the coplanar transmission line modes below the cut-off frequency.

The electrical connection to the metal enclosure should be continuous along the length of the electrodes to confine the modes within the ground plane. This can be achieved, for example, by bridging the gap between each of the pair of ground surface electrodes to the housing by a metallic grid. The grid will appear continuous if the mesh size is less than about 1/10 the microwave wavelength propagating between the hot electrode and the ground plane. The grid may comprise closely spaced bond wires.

The metal enclosure may be formed by metal-soldering metal bars to the base of a metal housing in which the optical modulator is to hermetically sealed. The optical modulator can then be fixed to the housing between the bars and the ground plane electrodes electrically connected to the bars as described above. The enclosure could be formed in other ways - for example by cutting a slot in a metal block.

Preferably, however, the ground plane electrode comprises a metallic layer on the surfaces of the substrate. This layer may be made in a series of separate coating operations. This structure minimises the dimensions of the single ground plane and thereby maximises the substrate mode cut-off frequency for a given substrate size by confining the microstrip modes entirely within the substrate.

Embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings of which

Figure 1 is a schematic cross-sectional view of a prior art, packaged optical modulator;

Figures 2 and 3 are graphs of the electrode transmission response for a Z-cut and X-cut Mach-Zehnder in the device package of Figure 1;

Figures 4 to 6 are schematic cross-sectional views of three embodiments of the present invention;

Figure 7 is a plan view of the submodule of Figure 5 as part of an experimental arrangement to measure the optical modulation response with frequency;

Figure 8 is of graph of the optical modulation response with frequency of the embodiment of Figures 5 and 7;

Figure 9 is a plan view of a further embodiment of the present invention in which the substrate has a metal coated ground plane; and

Figure 10 is a graph of the optical modulator response with frequency of the embodiment of Figure 9.

Referring the Figure 1, a prior art Mach-Zehnder optical modulator 2 comprises a Z-cut lithium niobate substrate 4 in which are formed in its upper surface 6 waveguides 8 and asymmetic electrodes for applying a modulated electric field across the waveguides 8, namely a ground plane electrode 10 and a hot electrode 12. The dimensions of the waveguides and electrodes are exaggerated for clarity. The substrate is fixed in a metallic sub-module 14 the ground electrode 10 being electrically tied to the sub-module 14 by a series of 10 ohm grounding resistors 16 of which only one is shown.

The submodule is mounted on a peltier cooling element 18 fixed to the base of a robust metallic device package 20 and hermetically sealed within the package 20 by a lid 22. The submodule housing contains dry nitrogen gas to provide a stable environment for the optical modulator 2.

One of two R.F. feed lines 24 is shown coupled to the hot electrode 12. The optical signal is coupled to the waveguides 8 via feedthrough (not shown) perpendicular to cross-sectional view of Figure 1.

Figure 2 shows the electrode transmission response of the Mach-Zehnder modulator of Figure 1. Resonant 'dips' 30 enter the spectrum at about 3 GHz. This is due to exitation of unwanted substrate modes removing power from the coplanar transmission line mode.

Figure 3 shows the resonant dips in an X-cut Mach-Zehnder optical modulator in the device package of Figure 1.

Referring now to Figure 4 an optical modulator 30 according to the present invention has the same waveguides 8 and electrodes 10 and 12 as the prior art modulator of Figure 1. A single ground plane electrode is provided which extends from near both sides of the hot electrode and bounds each side, 32, 34 and 36, of the substrate which extends substantially parallel with the active region of the hot electrode 12. In this embodiment the ground plane comprises a further surface electrode 38 and the side walls 40, 44 base 42 of a slot cut in a metal block 46, inthis case copper.

A unitary ground plane is formed by means of a closely spaced (§ 1mm) bond wires 47 coupling the electrodes 10 and 38 to the block 46. Other means of forming the electrical connections can be used, for example using a fine wire mesh ('gilder grid').

The block 46 is mounted on a peltier cooling element 18 fixed to the base of a robust metallic device package 20 and hermetically sealed within the package 20 by a lid 22 as in the Figure 1 embodiment.

Referring to Figures 5 and 7, an optical modulator 30 has a single ground electrode comprising gold plated metal bars 50 and 52 metal soldered to the base of a metal submodule housing 54. Electrical connections are made between the electrodes 10 and bars 52 and electrode 38 and bar 50 by metal bond wires (see Figure 7) as in the Figure 4 embodiment. Other materials way be used for the metallic bars may be used to form the ground plane electrode. Referring to Figure 7, the bars 52 have interposed a lithium niobate lead-in board 56 and a termination printed circuit board 58 which terminates the electrode transmission line in its characteristic impedance by means of two 50 ohm, thick film resistors 60 connected in

parallel and a dc current blocking capacitor 62 to allow for dc biasing of the electrode.

It can be seen from Figure 8, which shows the optical modulation response of the device of Figures 5 and 7, that the cut-off frequency is increased by about 3GHz, the first resonant dip occurring at 7GHz. The -3dB optical modulation point at 4.35GHz is very close to the theoretically predicted -3dB point of 4.33 GHz from consideration of the hot electrode length and the 9GHz on bandwidth length rule applicable to lithium niobate travelling wave devices. An X-cut lithium niobate Mach-Zehnder optical modulator was found to have an overall smoother roll off as the frequency increases and does not show a 1 dB roll off in the DC to 100 MHz region typical of Z-cut devices.

Referring now to Figure 6, a further embodiment of the present invention comprises the same optical modulator 30 in which the single ground plane is provided by all-round metallisation 64 deposited on the substrate 30 and electrically connecting the ground plane surface electrodes 10 and 38. This provides a ground plane of minimum dimensions and therefore maximum cut-off frequency for a given substrate size.

Figure 9 is an example of a Z-cut lithium niobate Mach-Zehnder optical modulator having all-round metallisation 70 of aluminium about a lithium niobate substrate 72 portions of which form upper surface ground electrodes 74 and 76 close to a hot electrode 78 (not separately visible on this scale). There is an 8mm long active region 80. The widths and gaps of the symmetic, coplanar active regions are 27µm and 9µm, respectively and chosen to match the optical guide geometry of Z-cut Mach-Zender devices. The RF lead-in 82, active region 80 and lead-out 84 have a characteristic impedance maintained throughout at approximately 22 ohms to reduce the affect the reflections from impedance mismatches. The width of

the device is 2mm to push the cut-off frequency for the substrate modes to at least 11.5 GHz.

Figure 10 shows the optical modulation response measured from 40 MHz to 20 GHz. The -3dB optical modulation bandwidth was measured at 11.6 GHz and the DC switching voltage was measured at 7.3V into a 20 ohm termination resistance. A bandwidth of 11.6 GHz appeared to indicate that the bandwidth-length rule at 9 GHz.cm had been broken, but in fact the performance was enhanced slightly by the impedance structure of the electrodes and package, where the resistive termination of 20 ohms was slightly lower than the characteristic impedance of the electrodes, estimated at 22 ohms. The first package resonance occurred at approximately 13 GHz, slightly above the substrate mode design cut off frequency of 11.5 GHz. The rather high switching voltage of 12.8V (as seen from a 50 ohm source) may be reduced further by fabricating the device on X-cut lithium niobate. An estimated switching voltage of 5.2V into 22 ohms, for an X-cut device, would give an apparent switching voltage of 8.5V when driven from 50 ohm source.

The present invention is not limited to the above specific embodiments but is applicable to other types of optical modulators employing travelling wave electrodes.

CLAIMS

1. An optical modulator comprising a substrate of an electrooptically active material having an optical waveguide and travelling wave electrodes including a hot electrode for applying an electric field to the optical waveguide in an active region extending in substantially one direction on a first surface of the substrate characterised in that there is single ground plane electrode which extends from near opposite sides of the hot electrode and bounds each surface of the substrate which extends substantially parallel with the active region other than the first surface.

2. An optical modulator as claimed in claim 1 in which the ground plane comprises a pair of ground electrodes on the first surface each electrically connected to a metal enclosure.

3. An optical modulator as claimed in claim 2 in which the metal enclosure comprises a pair of metal bars soldered to a metal support.

4. An optical modulator as claimed in claim 3 in which the metal enclosure comprises a slot formed in a metal block.

5. An optical modulator as claimed in any one of claims 2 to 4 in which the ground electrodes on the first surface are electrically connected to the metal enclosure by an electrically conductive grid.

6. An optical modulator as claimed in claim 1 in which the ground plane electrode comprises a metallic layer on the surfaces of the substrate.

7. An optical modulator as claimed in any preceding claim in which the substrate comprises lithium niobate.

Fig. 1.

PRIOR ART

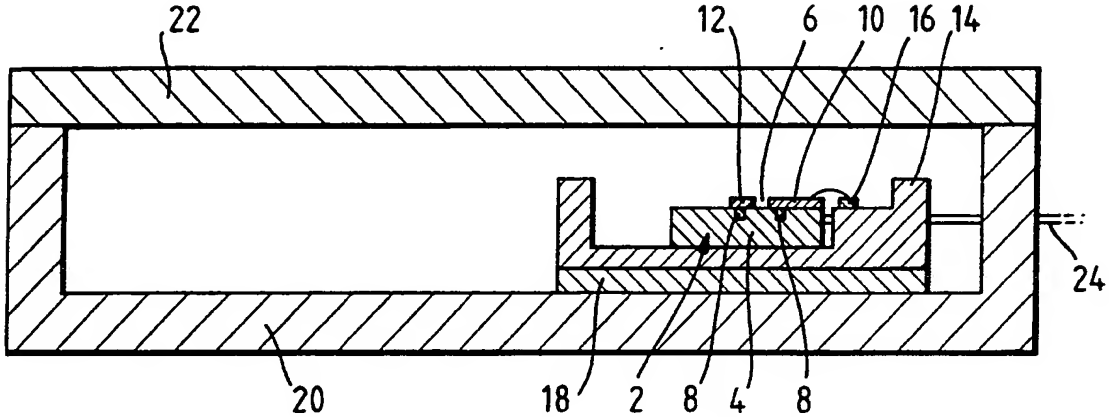
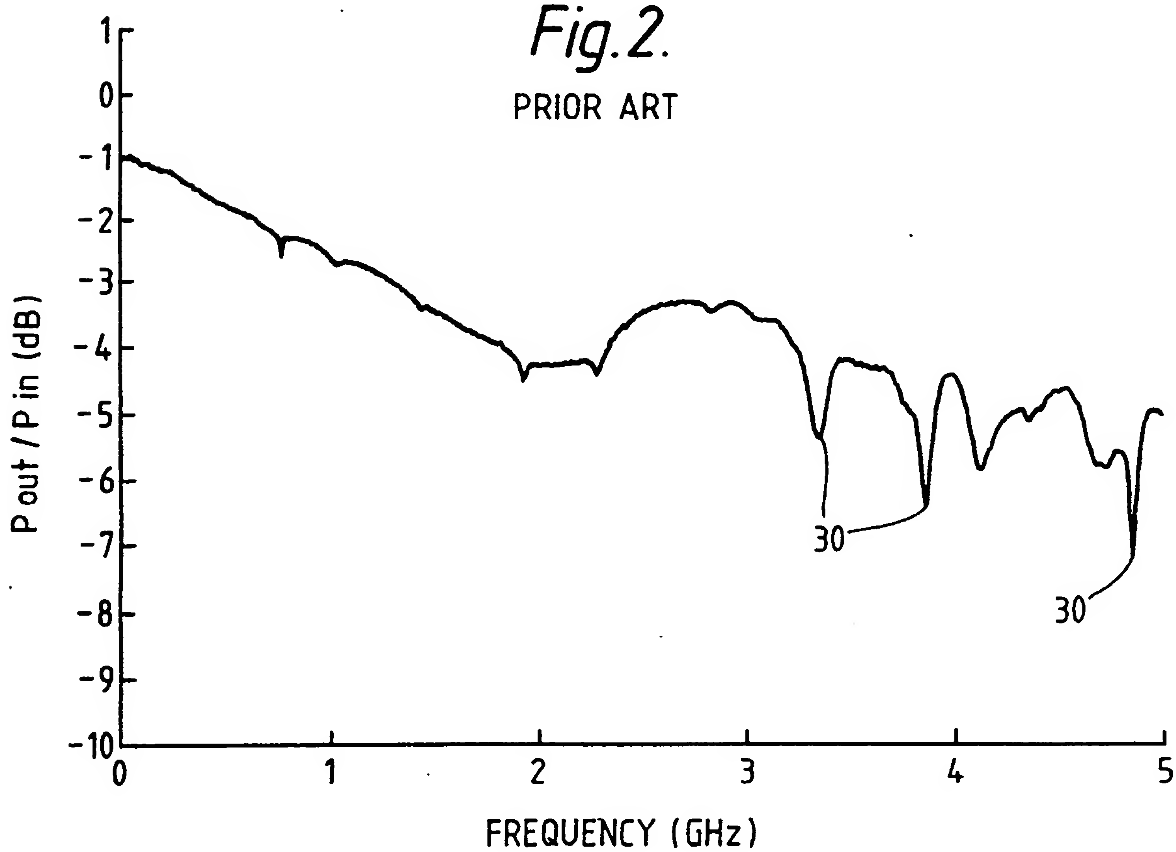


Fig. 2.

PRIOR ART



SUBSTITUTE SHEET

Fig.3.
PRIOR ART

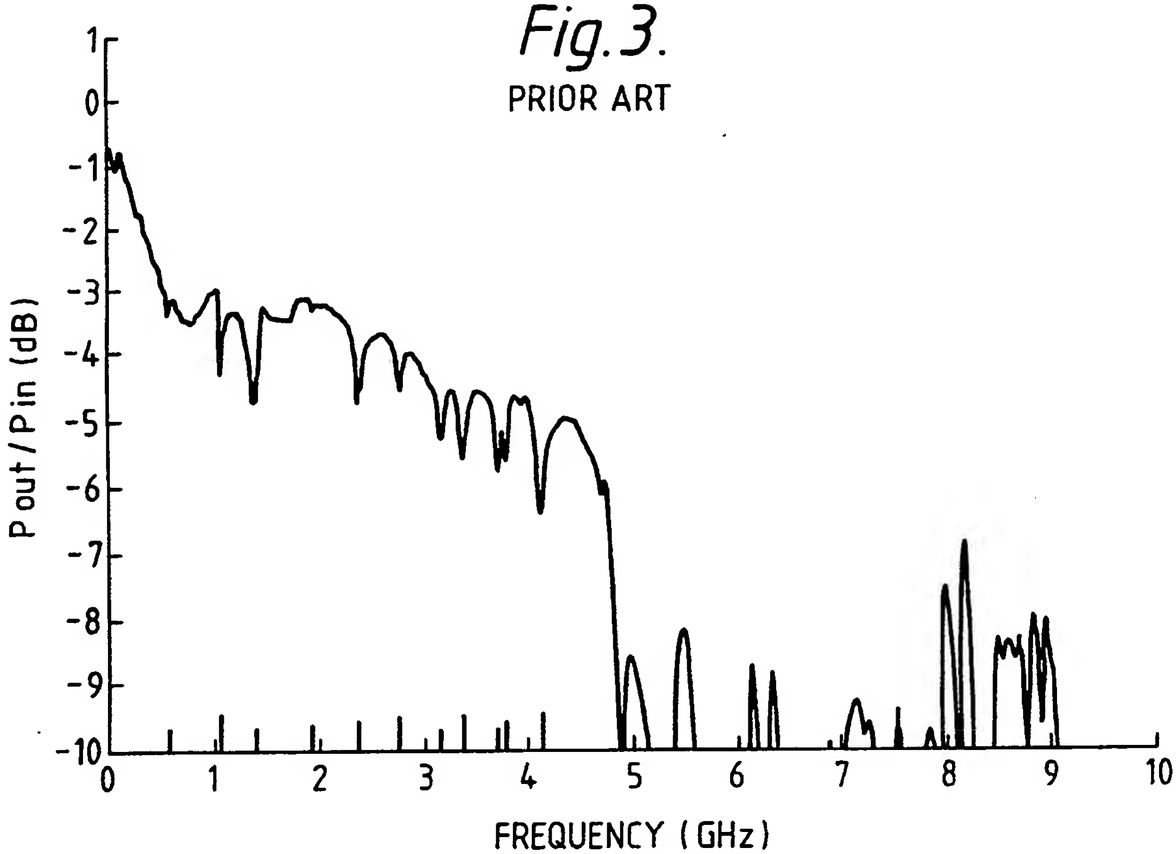


Fig.4.

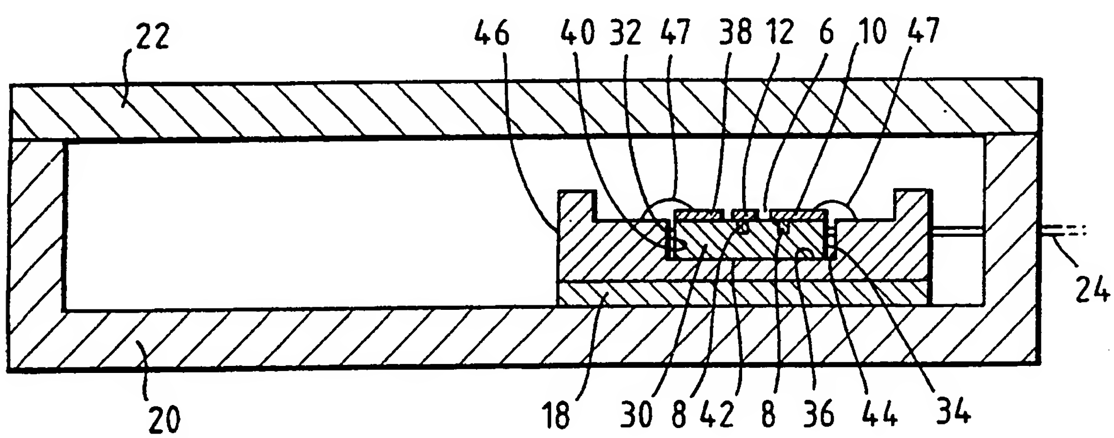


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Fig. 5.

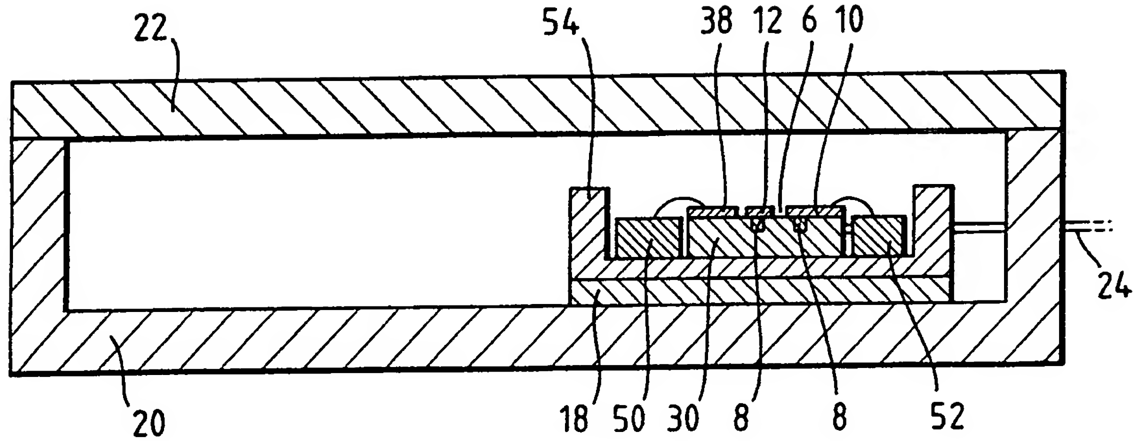


Fig. 6.

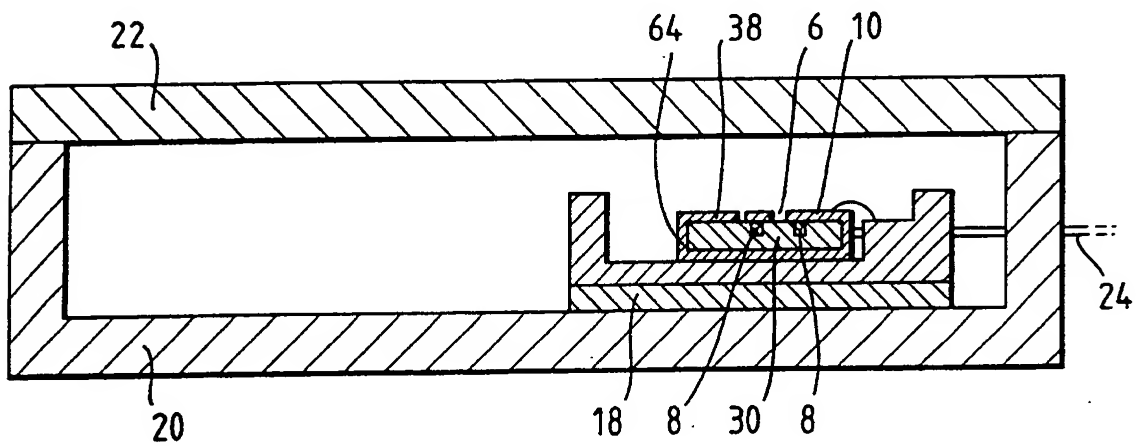


Fig. 7.

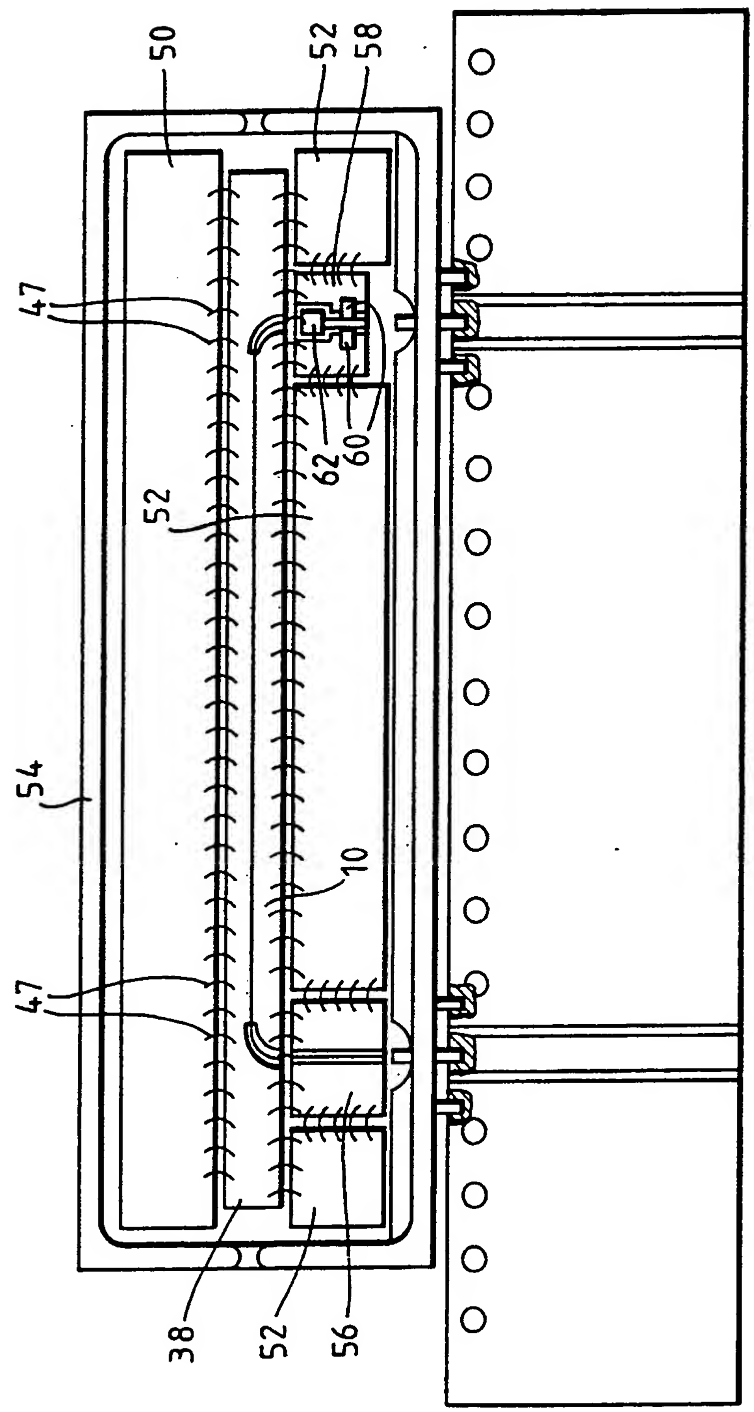


Fig.8.

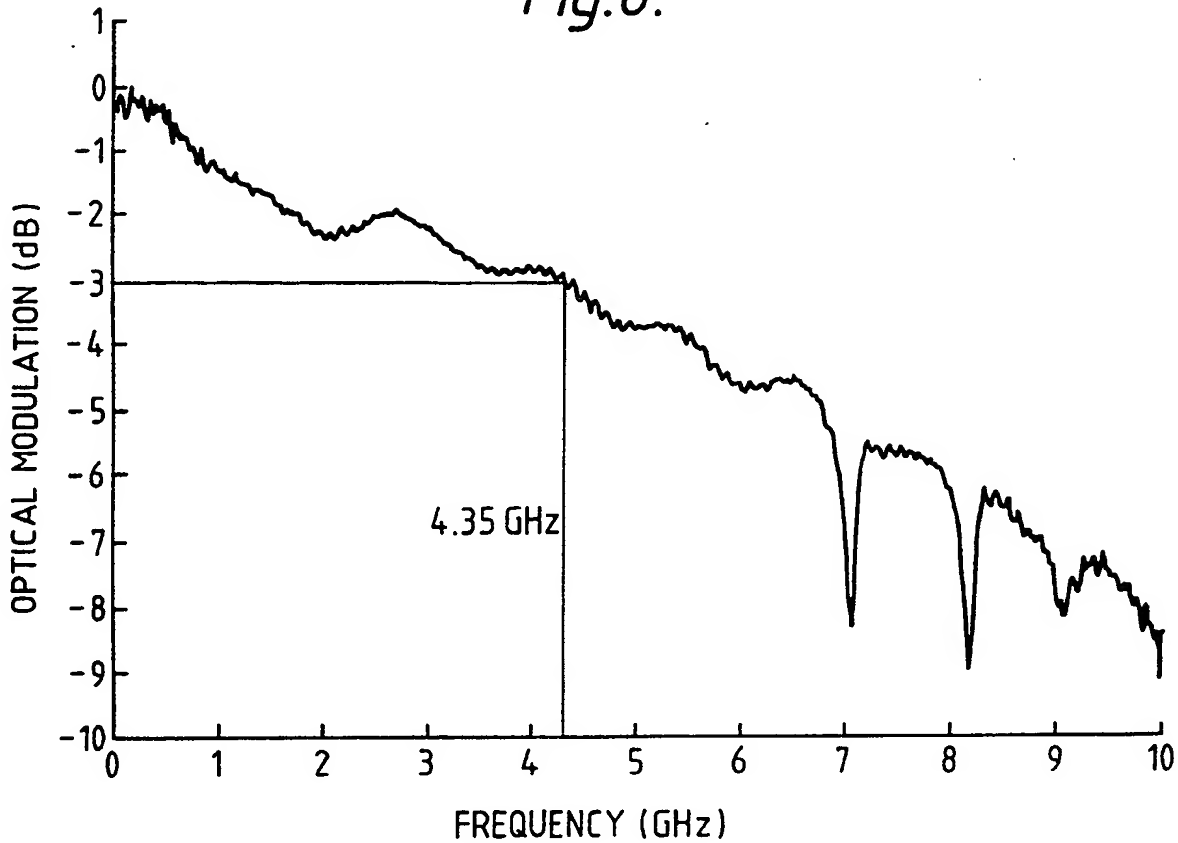

OPTICAL MODULATION (dB)
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
4.35 GHz
0
1
2
3
4
5
6
7
8
9
10
FREQUENCY (GHz)

Fig.9.

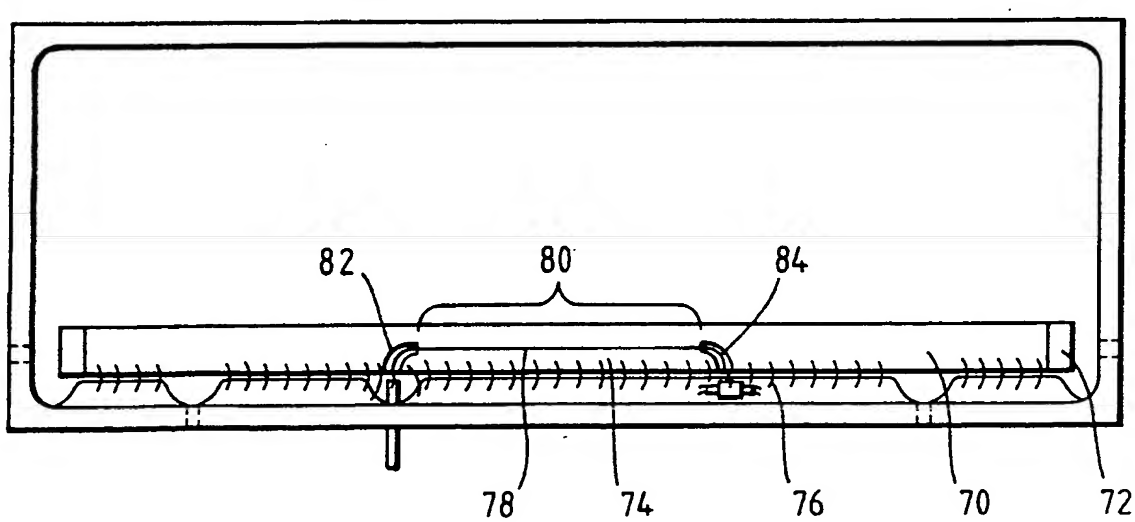
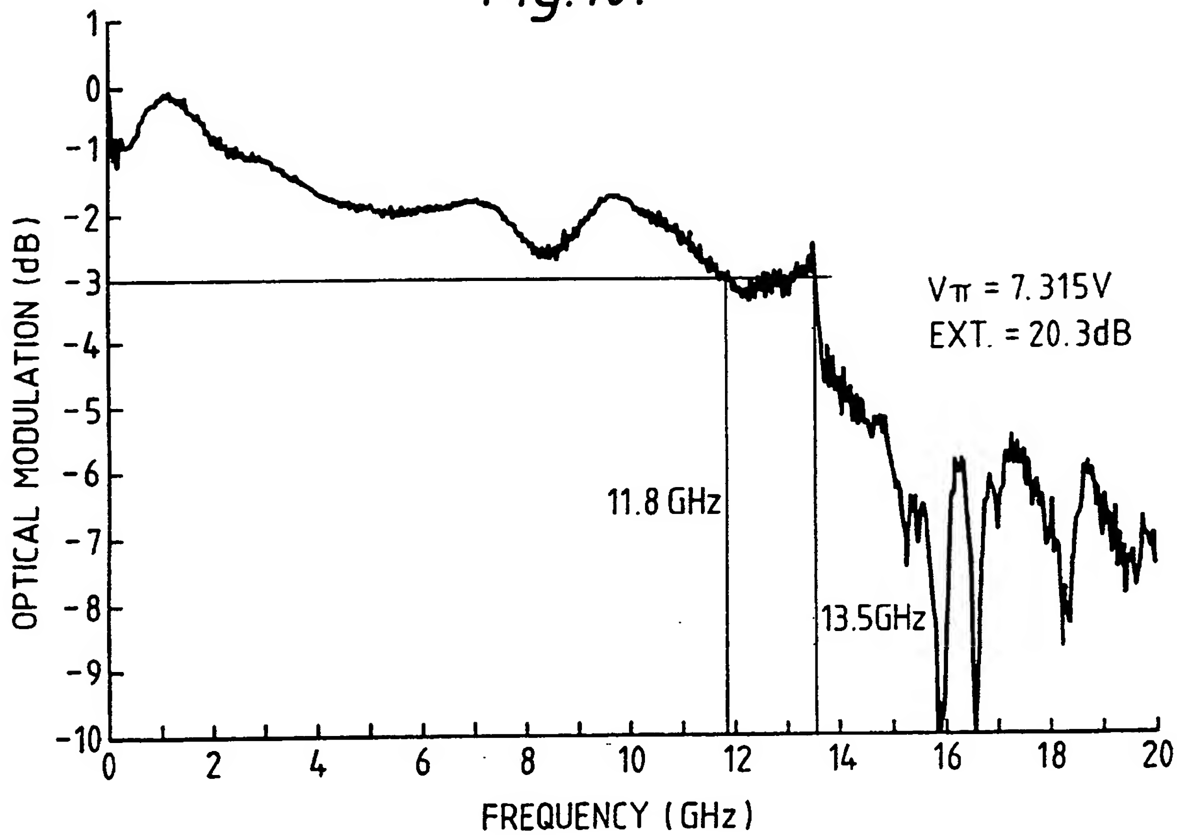

82
80
84
78
74
76
70
72

Fig. 10.


OPTICAL MODULATION (dB)
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
0
2
4
6
8
10
12
14
16
18
20
FREQUENCY (GHz)
11.8 GHz
13.5GHz
Vπ = 7.315V
EXT. = 20.3dB

International Application No

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl. 5 G02F1/035 ; G02F1/225

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
Int.Cl. 5	G02F

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III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category °	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No.[13]
A	WO,A,8 906 812 (E.I. DU PONT DE NEMOURS & CO.) July 27, 1989 see page 58 - page 62 ---	1
A	ELECTRONICS LETTERS. vol. 25, no. 20, September 28, 1989, ENAGE GB pages 1382 - 1383; K.KAWANO ET AL.: 'New travelling-wave electrode Mach-Zehnder optical modulator with 20 GHz bandwidth and 4-7V driving voltage at 1.52 um wavelength ' see figure 1 ---	1

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IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
06 AUGUST 1991	22.08.91
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	GALANTI M.

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)		
Category °	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No.
A	TRANSACTIONS OF THE I.E.C.E. OF JAPAN vol. E69, no. 4, April 1986, TOKIO,JP pages 415 - 417; M.IZUTSU ET AL.: 'Design Consideration for Guided-Wave Light Modulators with Coplanar Waveguide Type Electrodes ' see figure 1 ---	1
A	ELECTRONICS LETTERS. vol. 26, no. 5, March 1, 1990, ENAGE GB pages 318 - 320; A.DJUPSJÖBACKA: 'Novel type of baseband phase-reversal electrode for optical modulator with linear phase response ' see abstract ---	1

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO.

GB 9100704
SA 47190

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		AU-A- 3283489	11-08-89
		EP-A- 0396629	14-11-90

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